The unquenched quark model [1]

H. García-Tecocoatzi

Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, AP 70-543, 04510 México DF, México

Dipartimento di Fisica and INFN, Universitá di Genova, via Dodecaneso 33, I-16146 Genova, Italy

R. Bijker

Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, AP 70-543, 04510 México DF, México

E-mail: hugo.garcia@nucleares.unam.mx

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Abstract. In this contribution, we briefly analyze the formalism of the unquenched quark model (UQM) and its application to the description of several observables of hadrons. In the UQM, the effects of $q\bar{q}$ sea pairs are introduced explicitly into the quark model through a QCD-inspired $^3P_0$ pair-creation mechanism. We present our description of flavour asymmetry and strangeness in the proton when baryon-meson components are included. In the meson sector, the charmonium and bottomonium spectra with self-energy corrections due to the coupling to the meson-meson components .

1. Introduction

The quark model [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] can reproduce the behavior of observables such as the spectrum and the magnetic moments in the baryon and meson sector, but it neglects quark-antiquark pair-creation (or continuum-coupling) effects. Above threshold, these couplings lead to strong decays and below threshold, they lead to virtual $q\bar{q} - q\bar{q}$ ($qqq - q\bar{q}$) components in the hadron wave function and shifts of the physical mass with respect to the bare mass. The unquenching of the quark model for hadrons is a way to take these components into account.

Pioneering works on the unquenching of quark model were done by Törnqvist and collaborators, who used an unitarized QM [13, 14], while Van Beveren and Rupp used an t-matrix approach [11, 12]. These methods were used (with a few variations) by several authors to study the influence of the meson-meson (meson-baryon) continuum on meson (baryon) observables. These techniques were applied to study of the scalar meson nonet (a_0, f_0, etc.) of Ref. [12, 15] in which the loop contributions are given by the hadronic intermediate states that each meson can access. It is via these hadronic loops that the bare states become “dressed” and the hadronic loop contributions totally dominate the dynamics of the process. On the other hand, Isgur and coworkers in Ref. [17] demonstrated that the effects of the $q\bar{q}$ sea pairs in meson spectroscopy is simply a renormalization of the meson string tension. Also, the strangeness content of the

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nucleon and electromagnetic form factors were investigated in [18, 19], whereas Capstick and Morel in Ref. [20] analyzed baryon meson loop effects on the spectrum of nonstrange baryons. In meson sector, Eichten *et al.* explored the influence of the open-charm channels on the charmonium properties using the Cornell coupled-channel model [1] to assess departures from the single-channel potential-model expectations.

In this contribution, we discuss some of the latest applications of the UQM (the approach is a generalization of the unitarized quark model [11, 12, 14, 15]) to study the flavor asymmetry and strangeness of the proton, in wich the effects of the quark-antiquark pairs were introduced into the constituent quark model (CQM) in a systematic way and the wave fuctions were given explicitly. Finally, the UQM is applied to describe meson observables and the spectroscopy of the charmonium and bottomonium.

2. UQM

In the unquenched quark model for baryons [19, 21, 22, 23] and mesons [24, 25, 26, 27], the hadron wave function is made up of a zeroth order qqq ($q\bar{q}$) configuration plus a sum over the possible higher Fock components, due to the creation of $^3P_0$ $q\bar{q}$ pairs. Thus, we have

$$\begin{aligned} \mid \psi_A \rangle &= \mathcal{N} \left[\mid A \rangle + \sum_{BC\ell J} \int d\vec{K} \, k^2 dk \, \mid BC\ell J; \vec{K} k \rangle \right. \\ &\left. \qquad \frac{\langle BC\ell J; \vec{K} k \mid T^\dagger \mid A \rangle}{E_a - E_b - E_c} \right] , \end{aligned} \tag{1}$$

where $T^\dagger$ stands for the $^3P_0$ quark-antiquark pair-creation operator [24, 25, 26, 27], A is the baryon/meson, B and C represent the intermediate state hadrons, see Figures 1 and 2. E_a, E_b and E_c are the corresponding energies, k and ℓ the relative radial momentum and orbital angular momentum between B and C and $\vec{J} = \vec{J}_b + \vec{J}_c + \vec{\ell}$ is the total angular momentum. It is worthwhile noting that in Refs. [24, 25, 26, 27, 28], the constant pair-creation strength in the operator (1) was substituted with an effective one, to suppress unphysical heavy quark pair-creation.

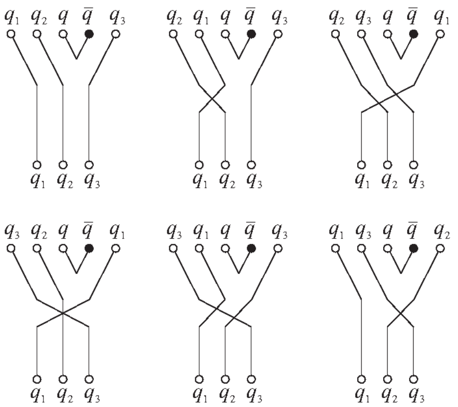

Figure 1. Quark line diagrams for $A \to BC$ with $q\bar{q} = s\bar{s}$ and $q_1q_2q_3 = uud$

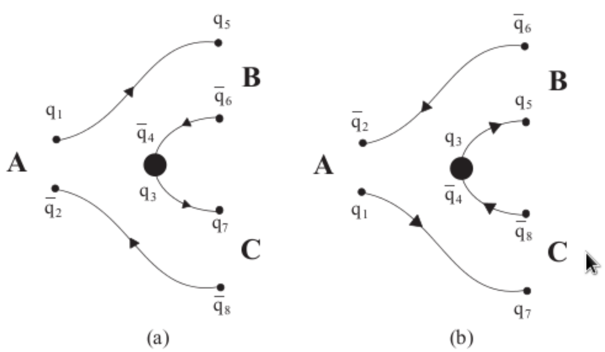

Figure 2. Two diagrams can contribute to the process $A \to BC$. q_i and q_i stand for the various initial (i = 1 - 4) and final (i = 5 - 8) quarks or antiquarks, respectively.

In the UQM the matrix elements of an observable $\hat{\mathcal{O}}$ can be calculated as

$$O = \langle \psi_A | \, \hat{\mathcal{O}} \, | \psi_A \rangle \ , \tag{2}$$

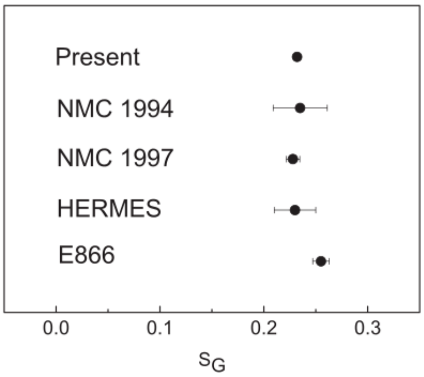

Figure 3. Comparison the value of Gottfried sum rule calculated within UQM with the experimental data from NMC 1994, NMC 1997, HERMES, and E866. Figure taken from Ref. [23]; APS copyright.

where $|\psi_A\rangle$ is the state of Eq. (1). The result will receive a contribution from the valence part and one from the continuum component, which is absent in naive QM calculations.

The introduction of continuum effects in the QM can thus be essential to study observables that only depend on $q\bar{q}$ sea pairs, like the strangeness content of the nucleon electromagnetic form factors [18, 19] or the flavor asymmetry of the nucleon sea [21]. In other cases, continuum effects can provide important corrections to baryon/meson observables, like the self-energy corrections to meson masses [24, 25, 26, 27] or the importance of the orbital angular momentum in the spin of the proton [22].

3. Flavour content in the proton

The first evidence for the flavor asymmetry of the proton sea was provided by NMC at CERN [29]. The flavor asymmetry in the proton is related to the Gottfried integral for the difference of the proton and neutron electromagnetic structure functions

$$S_G = \int_0^1 dx \frac{F_2^p(x) - F_2^n(x)}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 dx \left[\bar{d}(x) - \bar{u}(x) \right] \ . \tag{3}$$

Under the assumption of a flavor symmetric sea, one obtains the Gottfried sum rule $S_G = 1/3$. The final NMC value is 0.2281 ± 0.0065 at $Q^2 = 4$ (GeV/c)^2 for the Gottfried integral over the range $0.004 \leq x \leq 0.8$ [29], which implies a flavor asymmetric sea. The violation of the Gottfried sum rule has been confirmed by other experimental collaborations [30, 31]. Theoretically, it was shown in Ref. [32], that the coupling of the nucleon to the pion cloud provides a natural mechanism to produce a flavor asymmetry. In the UQM, the flavor asymmetry can be calculated from the difference of the probability to find $\bar{d}$ and $\bar{u}$ sea quarks in the proton

$$N_{\bar{d}} - N_{\bar{u}} = \int_0^1 dx \left[\bar{d}(x) - \bar{u}(x) \right] \ . \tag{4}$$

Note that, even in absence of explicit information on the (anti)quark distribution functions, the integrated value can be obtained directly from the left-hand side of Eq. (4). Our result is shown in Fig. 3.

The results for the two strangeness observables were obtained in a calculation involving a sum over intermediate states up to four oscillator shells for both baryons and mesons [19]. In

the UQM formalism, the strange magnetic moment of the proton is defined as the expectation value of the operator

$$\vec{\mu}_s = \sum_i \mu_{i,s} \left[2\vec{s}(q_i) + \vec{l}(q_i) - 2\vec{s}(\bar{q}_i) - \vec{l}(\bar{q}_i) \right] \tag{5}$$

on the proton state of Eq. (1), which represents the contribution of the strange quarks to the magnetic moment fo the proton; $\mu_{i,s}$ is the magnetic moment of the quark i times a projector on strangeness and the strange quark magnetic moment is set as in Ref. [23]. Our result is $\vec{\mu}_s = 0.0006\mu_N$(see Fig.4).

Similarly, the strange radius of the proton is defined as the expectation value of the operator

$$R_s^2 = \sum_{i=1}^{5} e_{i,s} \left(\vec{r}_i - \vec{R}_{\rm cm} \right)^2 \tag{6}$$

on the proton state of Eq. (1), where $e_{i,s}$ is the electric charge of the quark i times a projector on strangeness, $\vec{r}_i$ and $\vec{R}_{\rm cm}$ are the coordinates of the quark i and of the intermediate state center of mass, respectively. The expectation value of R_s^2 on the proton is equal to $-0.004{\rm fm}^2$. In Fig. 5 our result is compared with the experimental data.

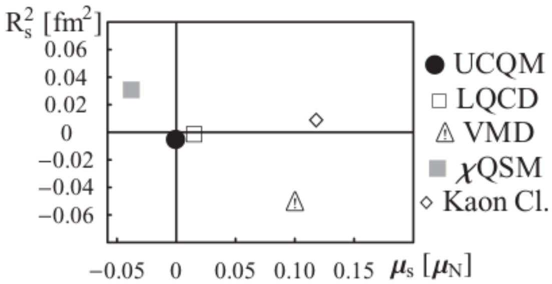

Figure 4. TheUQM results for the strange magnetic moment and radius of the proton. Figure taken from Ref. [19]; APS copyright.

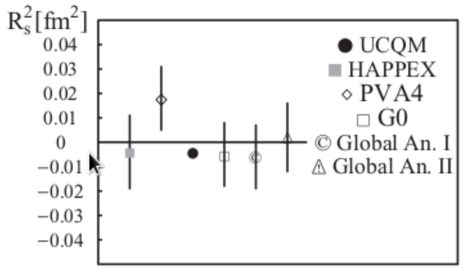

Figure 5. Comparison between our resulting value for the strange radius of the proton in the UQM. Figure taken from Ref. [19]; APS copyright.

4. Self-energy corrections in the UQM

In Refs. [24, 25, 26, 27], the method was used by some of us to compute the charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) spectra with self-energy corrections, due to continuum coupling effects. In the UQM, the physical mass of a meson,

$$M_a = E_a + \Sigma(E_a) \ , \tag{7}$$

is given by the sum of two terms: a bare energy, E_a, calculated within a potential model [3], and a self energy correction,

$$\Sigma(E_a) = \sum_{BC\ell J} \int_0^\infty k^2 dk \ \frac{\left| M_{A\to BC}(k) \right|^2}{E_a - E_b - E_c} \ , \tag{8}$$

computed within the UQM formalism.

Our results for the self energies corrections of charmonia [25, 27] and bottomonia [24, 26, 27] spectrums, are shown in figures 6 and 7.

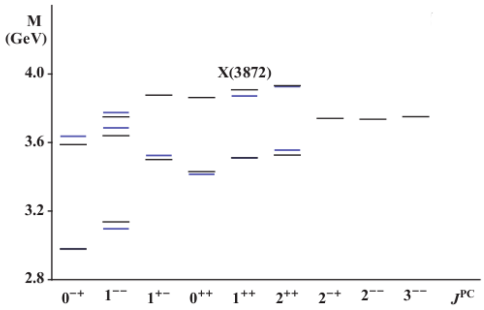

Figure 6. Charmonium spectrum with self energies corrections. Black lines are theoretical predictions and blue lines are experimental data available. Figure taken from Ref. [25]; APS copyright.

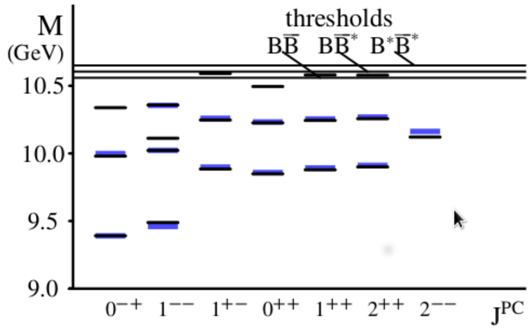

Figure 7. Bottomonium spectrum with self energies corrections. Black lines are theoretical predictions and blue lines are experimental data available. Figure taken from Ref. [26]; APS copyright.

5. Discussion and conclusion

In the baryon sector, our results for asymmetry and "strangeness" observables, as shown in Figures 3, 4 and 5, are in agreement with the experimental data. These observables can only be understood when continuum components in the wave function are included.

Our results in the meson sector for the self energies corrections of charmonium and bottomonium spectra, see figures 6 and 7, show that the pair-creation effects on the spectrum of heavy mesons are quite small. Specifically for charmonium and bottomonium states, they are of the order of $2-6\%$ and 1%, respectively. The relative mass shifts, i.e. the difference between the self energies of two meson states, are in the order of a few tens of MeV.

However, as QM's can predict the meson masses with relatively high precision in the heavy quark sector, even these corrections can become significant. These results are particularly interesting in the case of states close to an open-flavor decay threshold, like the $X(3872)$ and $\chi_b(3P)$ mesons. In our picture the $X(3872)$ can be interpreted as a $c\bar{c}$ core [the $\chi_{c1}(2^3P_1)$], plus higher Fock components due to the coupling to the meson-meson continuum. In Ref. [27], we showed that the probability to find the $X(3872)$ in its core or continuum components is approximately 45% and 55%, respectively.

In conclusion, the flavor asymmetry in the proton can be well described by the UQM. The effects of the continuum components on the "strangeness" observables of the proton are found to be negligible. Nevertheless, our results are compatible with the latest experimental data and recent lattice calculations. In the meson sector our self energies corrections for charmonia and bottomonia are found to be significant.

Acknowledgments

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